IMPACT OF HIGHWAYS ON AIR QUALITY

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A general survey is presented of the techniques by which the impact of highways on air quality may be measured and predicted. The processes by which air pollution emitted by moving vehicles is dispersed by atmospheric turbulence and transported by the wind are stated to be central to this problem. Application of micrometeorological theory and experience shows that the Richardson number is the most important parameter governing turbulent dispersion. The major existing theories available for the development of air quality models are discussed. An analysis is presented of a typical highway air quality impact study that included a measurement program and the development of a model to predict air quality in 1990. It is concluded that the measurement program was inadequate to verify the model and that little confidence could be placed in the future air quality projection. Four general conclusions are as follows: The microclimate is an important key to the problem of highway air quality because it determines the ability of the atmosphere to disperse air pollution and is closely related to land use patterns; the Richardson number should be a standard part of any air quality measurement program; better and more comprehensive measurement programs should have a higher priority than the development of more complex air quality models; and more attention should be paid to the inherent properties of the models.

•THE twentieth century has been a time of constantly increasing energy use in the United States and throughout the world. In the United States since 1925, the rate of increase has been about 3 percent per year. At the same time, there has been a major shift from coal to petroleum products as the major source of energy in this country and throughout the world. Pollution is inherent in the production and utilization of energy. With the second law of thermodynamics in mind, waste heat is the cleanest kind of pollution that can possibly be achieved. Of course, the relative efficiency of various kinds of energy production and use varies and is directly related to resultant pollution. In general terms, the most inefficient uses that we make of energy resources are the conversion process to electric power and transportation by means of the internal-combustion engine. In terms of waste heat and pollution, power generation and transportation lead all other categories.

The subject of this paper is pollution associated with transportation, in particular that emitted by motor vehicles traveling on highways. The processes that lead to a specified air quality level in the air that we breathe are complex. Figure 1 shows the kind of perspective that is useful in considering this problem. The diagram suggests that meteorological influences are highly important in determining air quality. In this paper, the meteorological aspect of the problem is emphasized, particularly the current state of our ability to model and predict the pollution emission to the air quality part of the process. Human health problems associated with air pollution will not be discussed.

Much of this paper is meant to have implications for and to be useful to the policy-making and planning processes in society. One of the benefits of making a diagram like Figure 1 is that it forces one to consider the problem from a broad perspective.

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From this point of view, it becomes clear that the processes that influence land use patterns are critically important in determining the net result of the entire human health and comfort system. The policy-making and planning processes are particularly important, for it is in this area that accurate information and estimates of the consequences of changes in specific portions of the system may have significant impact for the common good.

In this context, I would like to point out that the transportation industry has a unique role to play. In contrast to many protions of society, the advance planning component of transportation is strong and accustomed to making use of the best available engineering information in its operations. Consequently, the additional considerations that are necessary to protect and manage air quality come naturally to highway engineers and administrators. The transportation industry has an excellent opportunity to lead the way in rational planning to satisfy the immense demands that society makes for goods and services and also to protect environmental quality.

DISCUSSION OF THE PROBLEM

The problem of motor vehicle air pollution may be defined from a meteorological point of view as the transport and diffusion of material emitted from a line source near the surface of the earth. The problem is not really this simple, but the geometry strongly suggests this approach. One of the problems is that of scale. Like most complex systems, the factors that are important to small-scale processes in the atmosphere are very different from those that determine the larger scales. The phenomena that affect the transport and dispersion of highway pollution include, in meteorological terminology, the microscale and mesoscale. In this section, this distinction and its effect on highway air quality will be discussed.

Eschenroeder (7) has suggested the existence of a zone above highways in which the air is well mixed by the energy of the moving vehicles. This zone has the dimensions of twice the height of the average vehicle times the highway width and is called the mechanically mixed cell. This mixing zone or cell can be thought of as the cumulative effect of all the turbulent wakes that are formed behind each object moving along the highway. Within the mechanically mixed cell, pollution is supposed to be dispersed uniformly, to a first approximation, and this state is the effective initial distribution of air pollution that is acted on by micro- and meso-meteorological processes to affect air quality downwind of the highway.

It should be noted that, in this simple model, the quality of the air that drivers and passengers breathe directly above the highway is completely determined by the properties of the vehicles and their motors and is independent of meteorological processes. At sufficiently high winds, this certainly cannot be true. The extent to which the mechanically mixed cell is affected by external meteorological influences has not been studied in sufficient detail to allow any general statements at this time. This is an important point because it determines the pollution levels that highway travelers are subjected to and should be the object of an intensive experimental effort.

One operational conclusion that can be drawn from the mixing cell concept is that the effective height of emission of highway pollutants is the average height of the vehicles. For the remainder of this section, it shall be assumed that the actual highway emission pattern may be replaced by a line source concentrated at that height. This material, whether gaseous or particulate, is now subjected to the microscale wind transport and diffusion processes. Under most conditions, the wind near the ground varies logarithmically with height according to

$$U = \frac{U_*}{k} \ln \frac{z}{z_0} \tag{1}$$

where U is the wind speed at height z, k is the von Karman constant, U_* is a micrometeorological parameter called the friction velocity, and z_0 is the aerodynamic roughness and is directly related to the geometrical roughness of the surface. These last two parameters are important to the process by which atmospheric turbulence is generated near the ground. U_*, which is defined by

$$U_* = \sqrt{\frac{\tau}{\rho}} \tag{2}$$

where τ is drag force that the wind exerts on the surface and ρ is air density, can be thought of as representative of the turbulent velocity fluctuations that arise from the roughness of the surface and that do most of the work in diffusing material near the surface. The significance of the logarithmic wind law for highway air quality lies in the fact that, in all theoretical and empirical treatments of air pollution, air concentration is found to be inversely proportional to wind speed. Consequently, the air quality downwind of a freeway must be closely related to the effective height of emission, and an elevated highway configuration would be expected to result in significantly improved downwind air quality compared to at-grade highways. Again, this statement must be qualified by stating that highway measurements adequate to verify this prediction are only now being made.

An order-of-magnitude calculation has been made of the wind dilution effect on local air quality to be gained from elevating freeways. The effect of raising the highway to height z on the air concentration of pollution C at the same height at some arbitrary distance downwind was calculated (assuming a logarithmic wind profile and all other factors constant). The following relation was obtained:

$$\frac{100}{C}\frac{\partial C}{\partial z} = \frac{-100}{z \ln z/z_0} \tag{3}$$

If $z_0 = 0.1$ m, a value typical of suburban land use, this formula gives the following results:

Highway Height (m)	Percentage of Improvement per Meter Height	Highway Height (m)	Percentage of Improvement per Meter Height
1	43.5	6	4.1
2	16.7	7	3.4
3	9.8	8	2.9
4	6.8	9	2.5
5	5.1	10	2.2

As can be seen, large improvements in air quality immediately downwind would be expected for the first 1 or 2 m of elevation but with decreasing effect after that. It should be emphasized that this is only a rough order-of-magnitude estimate that neglects other effects, such as the mixing cell, which may be important or even dominate resultant air quality in some situations.

A second qualifying remark should be made at this point. The logarithmic wind law is strictly valid only for conditions in which the atmosphere is well mixed. Under other conditions, corrections must be made to this relation (21) that are, however, not large in magnitude and are well known; they provide a parameter called the Richardson number, which we will discuss in the following section.

At the same time that highway pollution is being transported by the wind, it is being diffused by atmospheric turbulence. It is useful to consider the energetics of turbulence at this point. The kinetic energy per unit mass e of the field of turbulence at a point may be defined as

$$e = \overline{\tfrac{1}{2}(u)^2} \tag{4}$$

where u is the turbulent component of the wind speed near the ground such that

$$U = \overline{U} + u \tag{5}$$

where $\overline{U}$ is the average wind speed. In both Eqs. 4 and 5, the bar signifies a spatial or a sufficiently long time average. Because turbulence is here considered as energy, it is instructive to look at the sources and sinks of turbulence energy near the ground. This problem was first treated by Richardson (28) who was particularly interested in the special case when turbulence vanishes in the atmosphere, a situation of critical significance to the air pollution problem.

The rate at which turbulence energy is generated mechanically by wind shear associated with surface roughness is given by (19)

$$U_*^2 \frac{\partial U}{\partial z} = K_m \left(\frac{\partial U}{\partial z}\right)^2 \tag{6}$$

where K_m is the turbulent diffusivity for momentum in the atmosphere and arises from the definition of U_*. The rate at which turbulence is suppressed by stable temperature gradients near the ground is given by

$$\frac{-g}{T}\frac{H}{\rho c_p} = \frac{g}{T} K_h \frac{\partial \theta}{\partial z} \simeq \frac{g}{T} K_h \frac{\partial T}{\partial z} \tag{7}$$

where g is the acceleration of gravity, T is air temperature in degrees Kelvin, c_p is the specific heat capacity per unit mass, H is the flux of sensible heat carried upward by turbulence (negative for stable conditions in which heat is diffused downward), K_h is the turbulent diffusivity for heat, and θ is the potential temperature, which in most practical cases may be replaced by temperature. It is apparent that the sign of this term changes if the sensible heat flux is upward, which corresponds to the normal condition during the day when heat is being transferred upward by convection from the warm ground. In this case, the temperature stratification is unstable, and turbulence is being generated by buoyant forces rather than being suppressed. For stable stratification, Richardson reasoned that turbulence would disappear when

$$\frac{g}{T} K_h \frac{\partial T}{\partial z} > K_m \left(\frac{\partial U}{\partial z}\right)^2$$

or

$$\frac{\frac{g}{T} K_h \frac{\partial T}{\partial z}}{K_m \left(\frac{\partial U}{\partial z}\right)^2} > 1 \tag{8}$$

that is, when the turbulence sink exceeds the source. The Richardson number Ri has come to be defined by

$$Ri = \frac{\frac{g}{T}\frac{\partial T}{\partial z}}{\left(\frac{\partial U}{\partial z}\right)^2} \tag{9}$$

where potential temperature must be used in the numerator if large height increments are used in evaluating the temperature gradient. Experimentally, it has been found that turbulence vanishes at Richardson numbers around 0.3 (34). The fact that the critical Richardson number is not unity reflects experimental observations (21) that the ratio K_h/K_m is considerably less than one under stable conditions.

In the years since Richardson's pioneering work, the parameter that bears his name has assumed an overwhelming significance in micrometeorology. It has been shown experimentally (6) and theoretically (1) that the Richardson number is the most important single parameter in all micrometeorological processes. That is, Ri is more important than, say, wind speed or the temperature stratification considered alone. In particular, the Richardson number has been found to be enormously useful in organizing data into simple and understandable patterns. Figure 2 shows some typical micrometeorological data organized into useful functional relations by the use of the Richardson number. In this figure, the "phi functions" are essentially correction factors giving the effect of atmospheric stability, as measured by the Richardson number, on the simple logarithmic profile formulas such as Eq. 1. ϕ_h refers to the vertical diffusion of heat, ϕ_w to water vapor, and ϕ_m to momentum. Because pollution diffuses by the same physical mechanisms, similar phi functions would be expected to apply to air quality models although no current model has reached this level of sophistication.

The Richardson number has the disadvantage that its numerical value varies with height so that measurements of this parameter must be made at a standard height to be comparable. Another equivalent parameter, more useful in some ways, may be obtained by forming the ratio of the two energy source-sink terms as before but now by using the most fundamental definition on the left of Eqs. 6 and 7:

$$\frac{\frac{-g}{T}\frac{H}{\rho c_p}}{U_*^2\frac{\partial U}{\partial z}} = \frac{z}{\left(\frac{-\rho c_p T U_*^3}{kgH}\right)} \qquad (10)$$

where the vertical derivative of the logarithmic wind law in this transformation is used. The quantity in parentheses, which has the dimension of length and is approximately constant with height, is called the Monin-Obukhov length L where

$$L = \frac{-\rho c_p T U_*^3}{kgH} \qquad (11)$$

Under stable conditions (downward, negative heat flux H), the Monin-Obukhov length has the interpretation of being roughly the height at which turbulence is suppressed. Under stable conditions, then, pollution emitted near the ground would be expected to diffuse to height L. Under very stable conditions, L becomes small, and air pollution concentrations are high. Under unstable conditions, L is negative and has the physical interpretation as being the height at which convectively produced turbulence energy compares with mechanically produced energy. Above L, convection predominates and, under these conditions, turbulence levels are higher, atmospheric diffusion is more efficient, and air concentrations of pollution are smaller.

In qualitative terms, it is permissible to visualize atmospheric dispersion as a process similar to molecular diffusion in a solid or liquid body. The random motion of the molecules acts on superimposed gradients to transport properties, such as heat, "down the gradient" from regions of high concentration to low. In the analogy with turbulent motion in fluids, turbulence is thought of as essentially random motion that acts to mix or equalize distribution of fluid properties, and, thus, the net result is a transport process in which one region of the fluid gains at the expense of another. Formally, diffusivity K_s of a fluid property s expressed in units per unit mass of fluid can be defined by

$$F_{sx} = -\rho K_s \frac{\partial c}{\partial x} \qquad (12)$$

where F_{sx} is the flux (transport per unit area and time) of s in the x-direction resulting from the diffusion process and c is the concentration per unit mass of air. The diffusivity so defined is formally equivalent to molecular diffusivity and, indeed, may be regarded as the sum of the molecular and turbulent processes. The size of the turbulent component of the diffusivity is, however, many orders of magnitude larger than the molecular term in natural fluid systems. The conclusion to be drawn is that turbulence is vastly more efficient at transporting fluid mass and associated properties, including pollution, than is molecular diffusion. That is the central significance of turbulence and also the fundamental reason for its existence.

The molecular analogy is useful only in a very general sense. Unlike molecular properties, such as conductivity or viscosity that can be tabulated as physical constants for many systems, turbulent diffusivity is a complex function of the state of the flow. It is, for instance, a function of the Richardson number. The property of turbulence that makes it particularly difficult to deal with both practically and theoretically is that the diffusivity cannot, in principle, be treated as constant even in situations where the measured Richardson number is constant. The reason is that diffusivity is observed to be a function of the scale of fluid motion. If one follows a puff of smoke emitted from a source near the ground, it is easy to observe a rapid increase of size of the puff as it entrains (mixes with) fluid from the environment. This process is a function of the energy that is contained in scales of motion (or "eddies") that are smaller than the puff. It is a fundamental property of the atmosphere and all turbulent flow systems that, if measurements are made of the amount of kinetic energy available in the various scales of motion present in the turbulence, it is invariably found that more energy exists at large scales than at small scales. Consequently, as our smoke puff grows, it is subjected to more and more energetic diffusion by the scales of turbulent motion smaller than its current dimensions. The larger it gets, the faster it diffuses. Richardson (29) was the first to recognize this remarkable phenomenon, and he proposed that this variation could be well represented by

$$K_s \simeq \text{constant} \times l^{4/3} \tag{13}$$

where l is a representative size of the "eddy" of identifiable diffusing substance. Richardson's law has stood the test of time and now constitutes a primary objective of any new turbulence theory.

There are several consequences of these properties of turbulence that are of significance to the practical objective of modeling the dispersion of pollution in the atmosphere. If one chooses to model the dispersion of effluent by following individual puffs or identifiable portions of the polluted air, it is not possible to consider the diffusivity as constant. Richardson's law must be taken into account. If one considers the distribution of turbulence energy with height above the surface of the earth, it is reasonable to expect that, as one gains altitude, larger and larger scales of motion will exist because there is more "room." This has been found to be true observationally (23) along with the logical corollary that diffusivity increases strongly with height. Hence, if the Richardson number at a given height is constant in time, it is permissible to consider the diffusivity as constant at that height. However, if the process extends over a considerable range in height, as diffusion does, the diffusivity is not a constant but a function of height. Thus, the common assumption in air pollution meteorology that the diffusivity is a constant quantity is an approximation whose limitations should be explicitly recognized.

The dispersion of particulates, large enough to fall out near their source, has certain unique properties. Because particulates emitted from any source have a spectrum of sizes, the fallout is differential; big particles reach the ground first. This effect alone, in the absence of any turbulence or wind shear, is enough to produce a wide dispersion of the material that falls out and is deposited at the surface of the earth. The terminal velocity is given as follows for various sized particles and simple order-of-magnitude calculation of the distance downwind at which a particle of the indicated size would be deposited if the average wind speed was 2 m/sec and the release height was 2 m.

Particle Radius (μ)	Terminal Velocity (cm/sec)	Deposition Point Downwind (m)
5	0.3	1,333
10	1.3	308
50	32.0	12.5
100	136.0	2.94
400	340.0	1.18

As can be seen, the dispersion due to differential fallout is considerable. This is also a stability-dependent process because the shape of the wind profile (and hence the average value of the wind) and the turbulent diffusivity between the release height and the surface are a function of the Richardson number.

The magnitude of the differential fallout effect is heavily dependent on the shape of the particulate size spectrum. Insufficient measurements have been made of the size distribution of particulates emitted by motor vehicles to allow modeling of this process with any degree of confidence.

The horizontal dimensions of cities are such that many properties of the atmosphere above them belong to those of the meteorological mesoscale. The term "air pollution meteorology" usually refers to the phenomena of the mesoscale, and, indeed, most air pollution studies have been concerned with this scale. The reason for making this distinction is that many of the fundamental properties of this scale of motion are different from those of the microscale. Table 1 gives a summary of the contrasting properties of the two scales from which their differing significances to pollution derive. Mesoscale wind systems arise because of horizontal gradients in the temperature of the earth's surface. Sea and lake breezes are familiar examples of this phenomenon. These wind systems have the properties that the strongest wind speeds are usually near the surface of the earth, and wind direction often exactly reverses with height. Figures 3 and 4 show examples of pollution transport in the Los Angeles basin by the sea breeze, and Figure 5 shows the typical reversal of wind direction with height. Because mesoscale wind systems are strongly associated with the 24-hour period of the sun, the wind flow develops slowly enough that the component of the earth's rotation about the local vertical (Coriolis parameter), which is a function of latitude, becomes an influence. Measurements of the Richardson number are difficult to make in the free atmosphere. Consequently, atmospheric stability is usually specified by means of the lapse rate alone. Elevated inversion (temperature increase with height) layers are usually present in diurnal wind systems, and the height of the base of the inversion is an important parameter for mesoscale air pollution modeling. Within inversion layers, the Richardson number often becomes large enough that all turbulence ceases, and hence inversions are effective barriers to atmospheric dispersion. Figure 6 shows a typical temperature sounding in the Los Angeles basin and the famous inversion layer that is usually present over that area during the summer and fall months.

In qualitative summary, it may be said that the most important physical processes and parameters that determine the concentration of pollution in the air that we breathe are the rate at which pollution is emitted into the atmosphere ("source strength"), distance downwind from the source of pollution, wind speed, atmospheric stability near the ground (Richardson number), height of elevated inversion layers, and topography.

MATHEMATICAL MODELING OF AIR QUALITY

In this section, the application of mathematical and numerical techniques to the problem of estimating air quality is discussed. With reasonable generality, the governing equation for the concentration C of some pollutant is

$$\frac{\partial C}{\partial t} = -u\frac{\partial C}{\partial x} - v\frac{\partial C}{\partial y} - w\frac{\partial C}{\partial z} + \frac{\partial}{\partial x}\left(K_x\frac{\partial C}{\partial x}\right) + \frac{\partial}{\partial y}\left(K_y\frac{\partial C}{\partial y}\right) + \frac{\partial}{\partial z}\left(K_z\frac{\partial C}{\partial z}\right) + R(t)C + S(x, y, z, t) \tag{14}$$

where u and v are the horizontal and w the vertical components of the velocity of the air in the x-, y-, and z-directions; K_x, K_y, and K_z are turbulent diffusivities associated with turbulent transport in the three coordinate directions; R(t) is a chemical reaction function for the case in which the pollutant is chemically active; and S(x, y, z, t) is a completely arbitrary source function that expresses the rate at which pollutant is emitted into a unit volume. Many different approaches can be adopted in obtaining analytic or numerical solutions to this equation. The most common solutions and methods that are currently in operational use in estimating air quality will be emphasized.

Figure 1. The air pollution system.

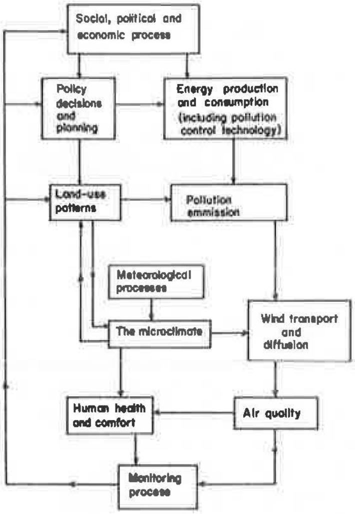


Figure 2. Micrometeorological measurements of the phi functions.

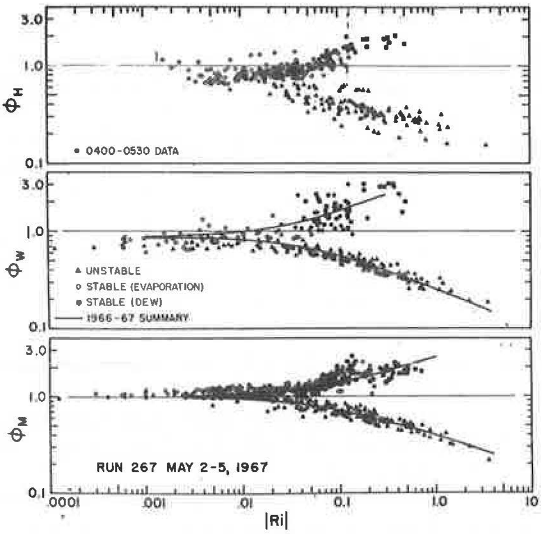


Table 1. Properties of microscale and mesoscale.

Phenomenon	Microscale	Mesoscale
Pollutant (primary gaseous and particulate pollutant)	—	Products of photochemical reactions
Space scale	1 to 100 m (highway corridor)	0.1 to 100 km (city, air basin)
Time scale	1 to 60 min	1 hour to 1 day
Primary transport processes (prevailing geostrophic wind)	Turbulence	Diurnal wind systems (sea breezes, etc.)
Source of transport energy	Surface roughness, wind shear, convection	Horizontal temperature contrasts, topography
Primary parameters (wind speed and surface roughness)	Richardson number	Latitude, stability (inversion height)
Typical model	Line-source Gaussian	Box

Figure 3. Los Angeles air flow pattern.

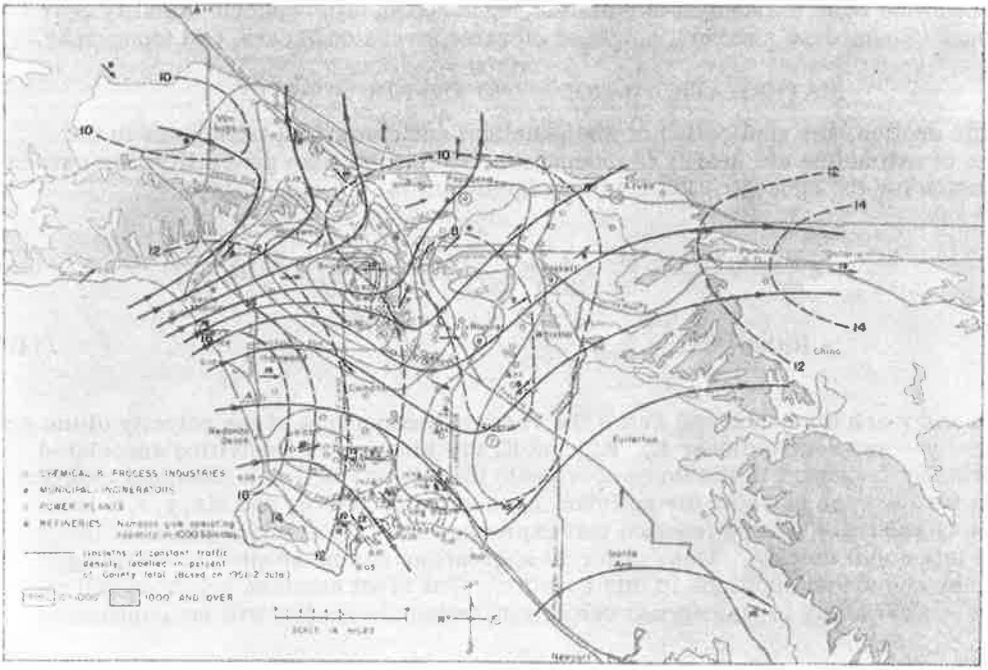


Figure 4. Los Angeles sea breeze.

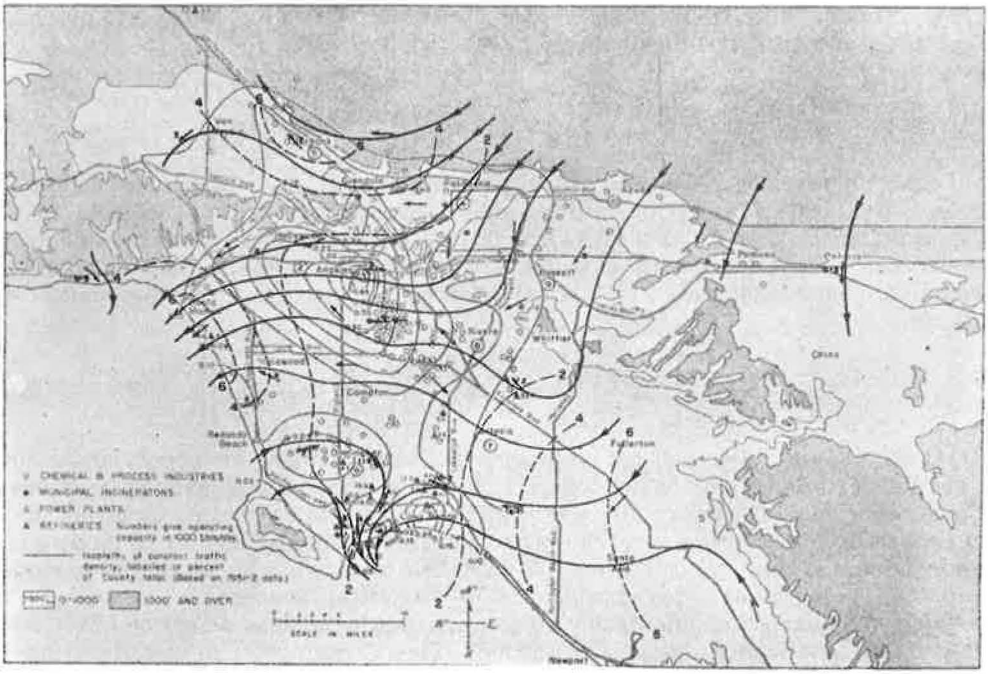
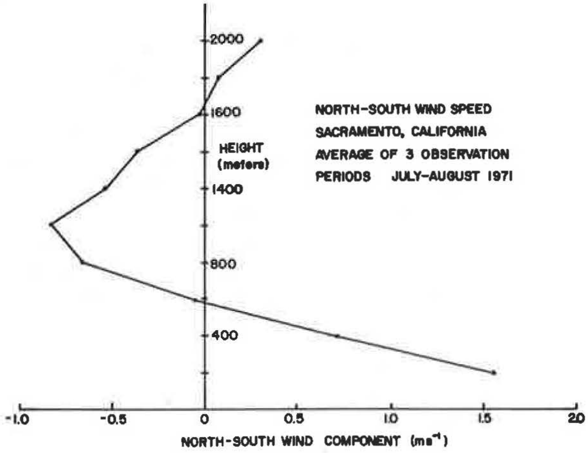


Figure 5. Mesoscale wind speed profile.



As it stands, Eq. 14 is formidable, and solutions are only possible if it is greatly simplified. For instance, if the mean wind is in the x-direction, vertical velocity is neglected, diffusion in the x-direction is neglected relative to wind transport, pollutant is nonreacting, and diffusivities are taken as constants, Eq. 10 reduces to

$$\frac{\partial C}{\partial t} = -u\frac{\partial C}{\partial x} + K_y\frac{\partial^2 C}{\partial_y^2} + K_z\frac{\partial^2 C}{\partial_z^2} + S(x, y, z, t) \tag{15}$$

For this case, application of boundary conditions appropriate for certain source configuration allows explicit analytic solutions to be found. Equation 15 is, in fact, essentially the molecular or Fickian diffusion equation, and numerous solutions are available in any text on heat conduction or molecular diffusion (4). For instance, one of the most commonly used solutions, which is valid for a point source of pollution emitted at height h, is

$$C = \frac{Q}{2\pi\sigma_y\sigma_z U}\exp\left[-\tfrac{1}{2}\left(\frac{y}{\sigma y}\right)^2\right]\left\{\exp\left[-\tfrac{1}{2}\left(\frac{z-h}{\sigma z}\right)^2\right]\exp\left[-\tfrac{1}{2}\left(\frac{z+h}{\sigma z}\right)^2\right]\right\} \tag{16}$$

where Q is the rate of release of the pollutant, $\overline{U}$ is the average wind speed, and σ_y and σ_z are the standard deviations of the concentration from the "plume" axis as functions of distance downwind. This formula is formally analogous to normal or Gaussian bivariate probability distribution, and the term Gaussian is usually applied to models that use equations of this type. Turner (35) used this solution in an air pollution model for computing the sulfur dioxide concentration in Nashville, Tennessee.

The key to the success of this or any other Gaussian formula is selection of the appropriate σ's as functions of distance downwind. These terms are, in fact, functions of the diffusivity and hence functions of surface roughness and atmospheric stability, as measured by the Richardson number. Turner (36) has published a practical system for making air quality estimates based on procedures developed by Pasquill (26) and Gifford (8). In this scheme, stability is estimated from meteorological conditions, such as wind speed, cloud cover, and intensity of solar radiation, in terms of six stability classes, A (strongly unstable) to D (neutral) to F (strongly stable). The dispersion parameters σ_y and σ_z are then taken from graphs that specify downwind variation as a function of stability. Figure 7 shows the set of curves for σ_z.

Equation 16 includes the assumption that the surface acts like a perfect reflector; i.e., no deposition or absorption takes place. Clearly, this assumption is appropriate only for chemically inactive gases. The presence of elevated inversion layers can be handled by assuming that, when the plume dimensions have become comparable to the height of the base of the inversion H, this becomes a lid preventing further vertical growth, and thereafter mixing in the vertical is complete. If this distance downwind is assumed to be twice that at which one-tenth of the plume has penetrated the inversion, then the formula for air concentration becomes

$$C = \frac{Q}{\sqrt{2\pi}\,\sigma_y H\overline{U}}\exp\left[-\tfrac{1}{2}\left(\frac{y}{\sigma_y}\right)^2\right] \tag{17}$$

where the concentration is now independent of the vertical direction, and this relation is supposed to be valid when $\sigma_z > 0.94$ H.

The Gaussian approach is easily extended to other source configurations. For a continuously emitting infinite line source, the solution at ground level is

$$C = \frac{2Q}{\sqrt{2\pi}\,\sigma_z U\sin\phi}\exp\left[-\tfrac{1}{2}\left(\frac{h}{\sigma_z}\right)^2\right] \tag{18}$$

where ϕ is the angle between the wind direction at the line (zero at right angles).

Equations 16 and 18 are the working formulas for the great majority of practical schemes for estimating air concentration from air pollution source inventory informa-

Figure 6. Sounding of temperature and humidity over Los Angeles.

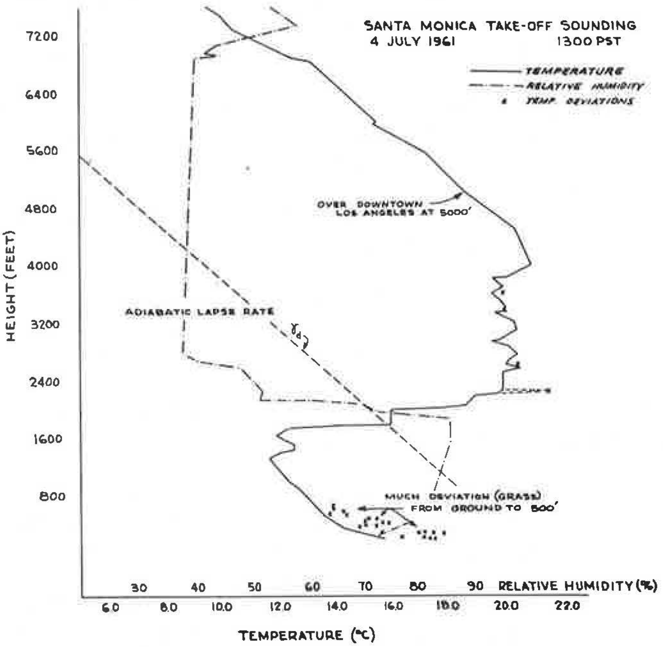
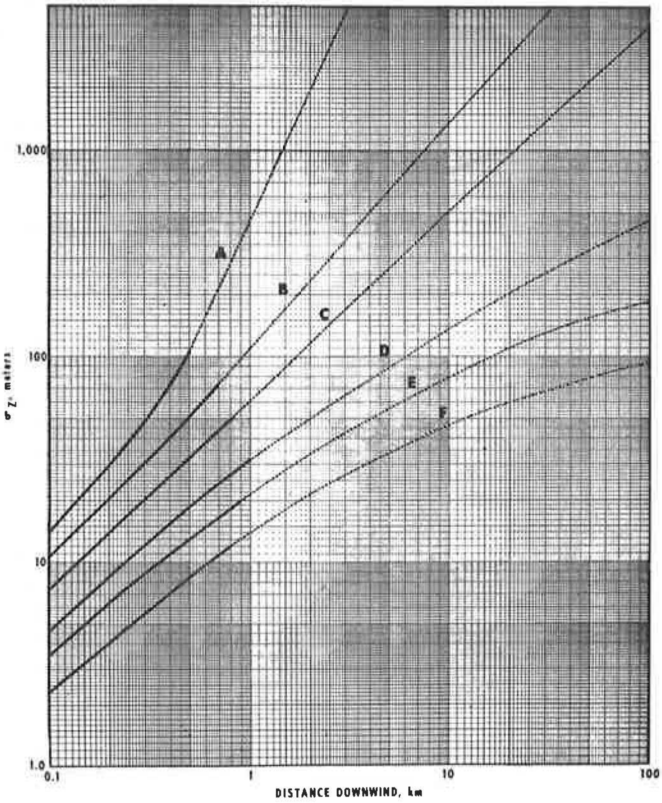


Figure 7. Vertical dispersion coefficient as a function of downwind distance from the source.



tion. Calculating the air concentration at a specific point in an urban area is done by dividing the city into a set of equal areas defined by a grid and assigning an appropriate source strength to each. For instance, in his Nashville study, Turner (35) obtained SO_2 source strengths for each square mile in a 17- by 16-mile rectangle. Downwind concentrations resulting from SO_2 emitted within a given square mile were calculated from the point source formula, assuming that the area emission was concentrated at a point. This calculation was repeated for each of 272 square-mile sources, and the results were counted to give the net result. Observed wind speeds and σ's estimated from observed meteorological conditions were used. Comparison between observed and computed 24-hour averages showed that 58 percent of all computed values were within ±1 pphm, a result that was taken as demonstrating the feasibility of the approach.

Several other investigators have made calculations similar to those of Turner. Koogler et al. (16) used Turner's equation with the addition of an exponential decay to account for SO_2 removal processes for Jacksonville, Florida. Koogler obtained 95 percent of his calculated SO_2 concentrations within ±1 pphm of observed values. Hilst (14) used essentially the same approach for the state of Connecticut, using an improved method of incorporating observed winds; 5,600 square area sources were used, each 5,000 ft on a side, and important individual sources, such as large power plants, were treated individually.

The most sophisticated air pollution model now in existence is the one being developed by Lamb (17) and Neiburger. This model includes improved solutions to the diffusion equation for point, finite line, and area sources, absorption of pollutants at the ground, simple chemical reactions whose rates may be given as arbitrary functions of time, and horizontally and time varying winds. In this model, the diffusion coefficients are constants, wind does not vary with height, and vertical motion is neglected. Preliminary calculations with this model, using observed winds and traffic data, were made for carbon monoxide. The results, although considered encouraging, revealed a major source of error associated with the neglect of vertical motion. Unrealistically large values of carbon monoxide concentration were calculated to occur in regions of horizontal convergence of the wind, indicating that removal of pollutant by vertical motion is an important process that cannot be neglected. This model is in an active state of development, and important and high-quality results are anticipated in the near future.

In addition to the Gaussian models and Neiburger and Lamb's improved version of this technique, there are four other major approaches to the problem of calculating air quality from measurable parameters. One is based on the statistical theory of turbulence, originally introduced by Taylor (33). In this approach, emphasis is placed on the statistical properties of velocity fluctuations of ensembles of passively floating particles or marked fluid. The statistical theory deals directly with the spread of a group of particles with respect to a frame of reference moving with the fluid (Lagrangian frame), which is the most fundamental manner in which to treat turbulent diffusion. Because measurements are almost always made with respect to a fixed (Eulerian) frame of reference, a central problem in applying the statistical theory to practical dispersion problems is to establish the correspondence between Lagrangian and Eulerian turbulence parameters. The statistical theory may be the most fundamental approach but is probably the most remote from immediate practical application at this time.

Another major approach that is only now being developed and hopefully represents a useful compromise between the unashamed empiricism of the Gaussian models and more satisfying basic theory is the hydrodynamics approach. In this technique, the fundamental equations of meteorological dynamics and thermodynamics are numerically solved on a three-dimensional grid using approximate topography as a boundary condition to provide the mesoscale flow and stability. Smaller scale flow features, or "turbulence," are handled by means of diffusivity parameters. A less satisfying variant of this approach would be to use observed three-dimensional winds to specify the mesoscale flow. This alternative appears less satisfying because of the extraordinary measurement problem.

Three-dimensional numerical integrations are so demanding of computer storage and computational speed that only relatively crude models can be solved at this time.

It remains to be seen whether computer capabilities develop fast enough for this approach to be of practical utility in the near future.

The next of the major approaches to the problem is the similarity theory, introduced by Monin (20) and developed further by Batchelor (3), Gifford (9), and Pasquill (27). In this technique, a semi-empirical framework based on dimensional analysis is adopted to organize pollutant data in terms compatible with micrometeorological practice. The similarity theory is the newest of major approaches to the problem of turbulent diffusion of pollution emitted near the surface of the earth. It is the only theory that now permits direct application of standard micrometeorological procedures and parameters such as the Richardson number. At this time, however, the similarity theory has not been worked out for a sufficient variety of source configurations to allow immediate incorporation into practical air pollution models.

The last approach to be discussed here is the so-called box model, which is very simple but nevertheless useful for mesoscale applications. In situations where a well-defined inversion acts as an effective lid on vertical dispersion and when pollution is emitted more or less uniformly over a large urban area, it may often be acceptable to calculate concentration from

$$C = \frac{kQ}{\overline{U}H} \tag{19}$$

where $\overline{U}$ is the average wind speed between the surface and the height of the base of the inversion, k is a constant, and Q is an emission rate per unit area. Hanna (11) has shown that simple formulas like Eq. 19 are often as accurate as much more sophisticated approaches.

The modeling approaches that have been discussed are meant to be used in a practical engineering sense. They must ultimately be judged in this spirit. Before attempting an overall evaluation of the state of the art of highway air quality modeling, it is instructive to look at an operational attempt to use some of the techniques presented.

During the past 2 years, the California Division of Highways has been conducting an extensive environmental impact program to evaluate the effect on air quality of current highways in the state and to make projections of the effect of future planning decisions regarding highway construction. At present, this program is limited to an evaluation of the probable air quality impact of the decision to build or not to build highways whose routes and configurations were planned well before the overriding significance of environmental impact became clear. There were four major objectives of the program. One was to generate reliable data on the current state of air quality near highways. The second objective was to develop and verify practical highway air quality models. The third was to develop models for assessing highway impact on the air quality of entire mesoscale air basins. The fourth was to use verified models to estimate air quality in 20 years' time for the built and not-built cases for particular highway plans. At present, several contracts have been awarded to research and development groups in the private sector to perform these impact studies. Following is a brief outline of the results of the first of the studies to be completed, which was an air quality analysis and impact study of proposed Cal-92 and -238 near Hayward, California.

The Hayward area lies on the coastal plain to the east of the southern portion of the San Francisco Bay. The immediate topography is uncomplicated; on a larger scale, Hayward lies in the basin that encloses the bay. The firm that was awarded the contract collected all available air quality and meteorological data for the area, established additional meteorological and air pollution monitoring stations, developed a Gaussian transport and diffusion model, verified the model with data taken during a special concentrated observation period, and performed calculations with the model to estimate air quality in the region for 1990 with and without the proposed freeways. On the whole, there is no doubt that this was a highly professional piece of applied science and is well representative of the current state of measurement techniques and modeling capability. For these reasons, whatever criticism is made, the techniques employed or results obtained in this study are to be taken as applying to the field as a whole.

Figure 8 shows an example of the basic data that were collected in the Hayward area by the contractor. The pollutant is carbon monoxide averaged over 24 hours. The numbers attached to the data points refer to the various sites used in the study. The extreme day-to-day variability is typical of pollution data. The horizontal dashed line is the ambient air quality standard for carbon monoxide (12 hours at 10 ppm). Figure 9 shows a cumulative frequency diagram derived from the 1,063 hourly measurements of carbon monoxide made during the $2\frac{1}{2}$ months of this study. The figure shows, for instance, that hourly average carbon monoxide concentrations of 10 ppm were equaled or exceeded 18 percent of the time during this study. Figure 10 shows the noncumulative frequency distribution for the same data but now broken down by site. The variability from site to site and the apparent bimodal character of these curves are striking. In addition, it could be said that these curves do not have the usual smooth appearance of well-defined and stable statistics. The question must be asked as to whether the conditions of this study allowed time for sufficient data to be gathered to allow reliable statistical generalizations to be made. Figure 11 shows a similar analysis of weekday versus weekend data for all sites.

The investigators state that, although the analysis is not presented in sufficient detail to allow evaluation, a significant correlation was found between carbon monoxide and the product $\overline{U}H$, where these parameters have the same meaning as in the box-model approach discussed previously, so that the result amounts to partial validation of that approach.

Figure 12 shows a summary of a concentrated microscale study in the immediate vicinity of an existing freeway section that ran approximately north-south. All data are shown from a variety of meteorological and traffic situations, and it is difficult to see a clear pattern such as simple models (e.g., the line-source Gaussian) would lead you to expect. Figure 13 shows a typical individual case for downwind data and Figure 14 for upwind data. Although these displays appear to be more reasonable than the previous scatter diagram, serious methodological questions arise from consideration of these data. The measurements were made by moving a van containing air pollution sensing apparatus from point to point. Thus, the data are not simultaneous and contain large variations of meteorological parameters from point to point. Such a procedure would not be acceptable in any professional micrometeorological study. Measurements must be simultaneous to be comparable. The contractor did the best job possible with the time and resources available; however, a better job needs to be done.

A validation analysis was made of the highway diffusion model. The objective was to estimate the contribution to carbon monoxide concentration at specific locations from an existing freeway alone. The background concentrations were larger than the calculated freeway contributions. It is difficult to have confidence in the modeling approach on the basis of this analysis alone.

An additional criticism can be made concerning the lack of analysis of the properties of the model itself. At a minimum, a sensitivity analysis of the operational model should be made to determine the relative importance of the various input data and the degree of precision needed. For instance, how sensitive are the validation calculations to uncertainties in, say, the wind speed or freeway emission rate? Without such information, it is difficult to interpret a validation analysis.

To fulfill the final portion of the study, the contractor used the developed models to make air quality projections for 1990. On the mesoscale, a number of calculations were made for various wind directions and stabilities for the cases in which the proposed Cal-92 and -238 were built and not built. In general, the mesoscale calculations showed little difference between these two cases.

On the microscale, within 1,000 ft of the highway corridor, relatively large differences were found between the built and not-built cases. Figure 15 shows typical results that indicate lower upwind concentrations of carbon monoxide and considerably higher downwind concentrations of carbon monoxide for the built case in comparison with the not-built one. In view of the uncertainties in the validation program discussed previously, it becomes doubly uncertain as to how to interpret or use these microscale projections. An important point to note is that these calculations are presented, as is appropriate, in the form of air concentrations at various distances from the freeway. The

Figure 8. Time variation of carbon monoxide concentration.

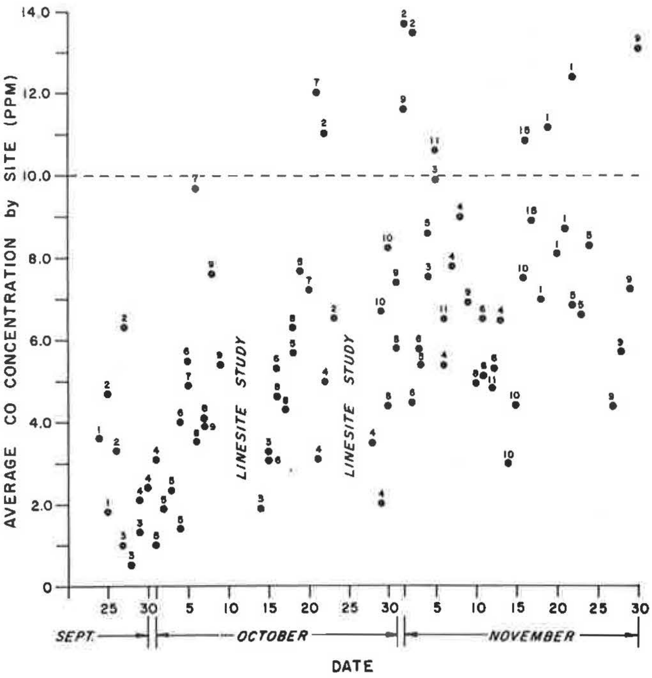


Figure 9. Cumulative probability distribution for carbon monoxide concentration.

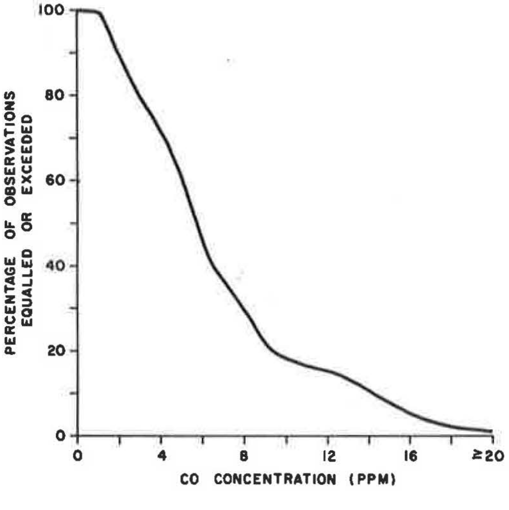


Figure 10. Carbon monoxide frequency distribution.

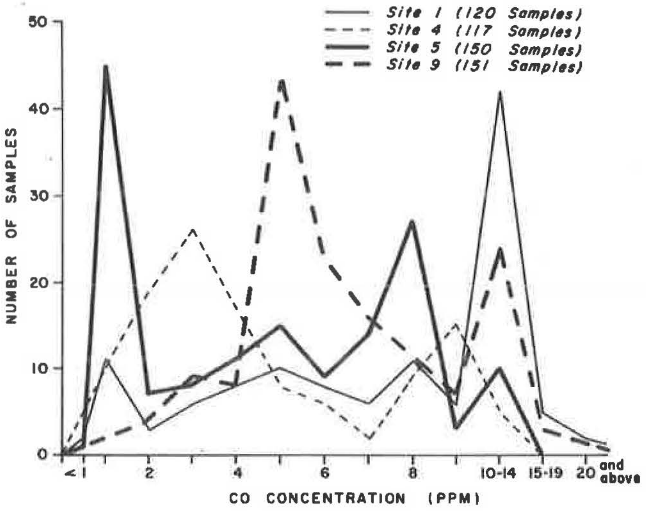


Figure 11. Frequency distribution of carbon monoxide concentration.

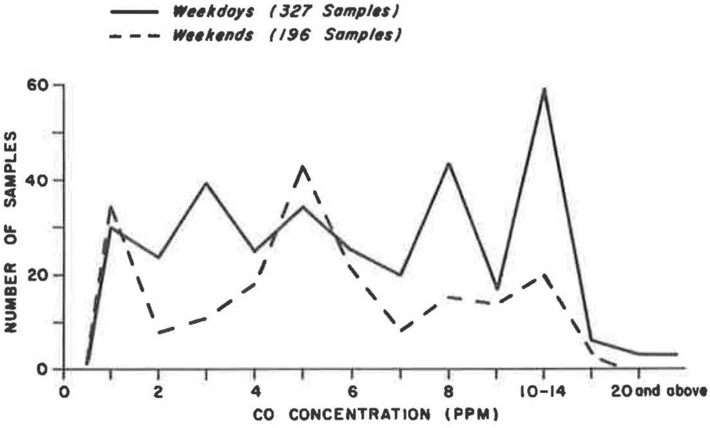


Figure 12. Carbon monoxide concentration near Nimitz Freeway.

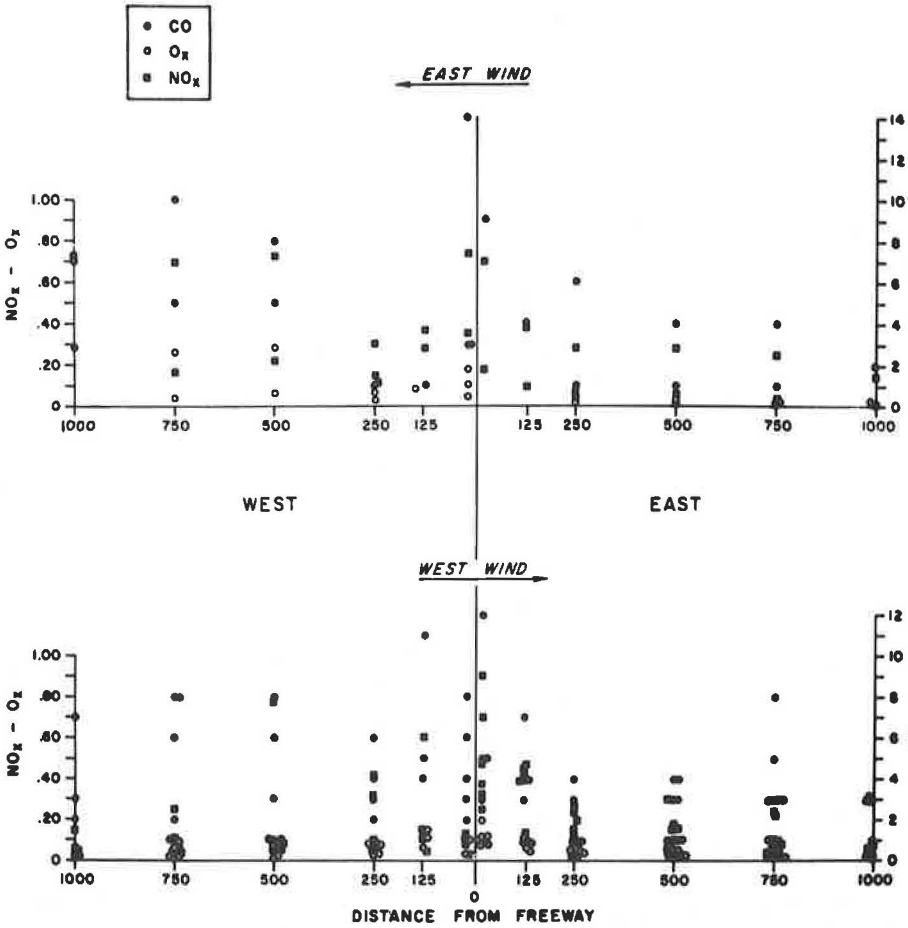


Figure 13. Pollution measurements made upwind of Nimitz Freeway.

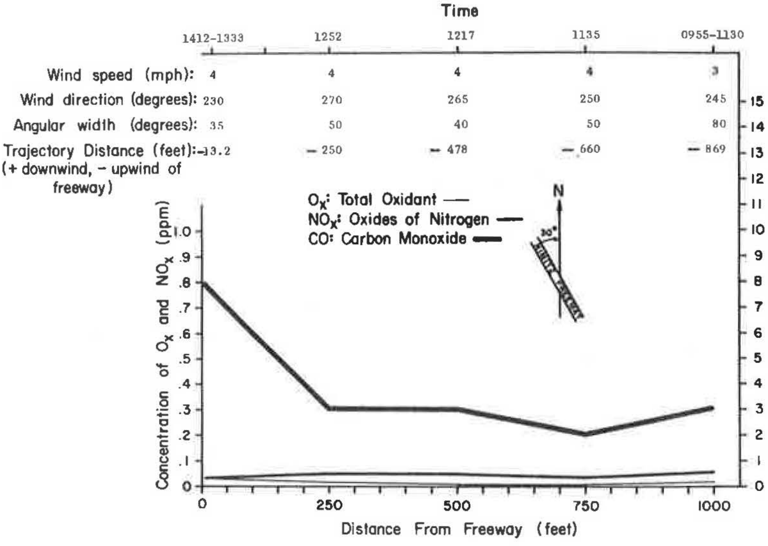


Figure 14. Pollution measurements made downwind of Nimitz Freeway.

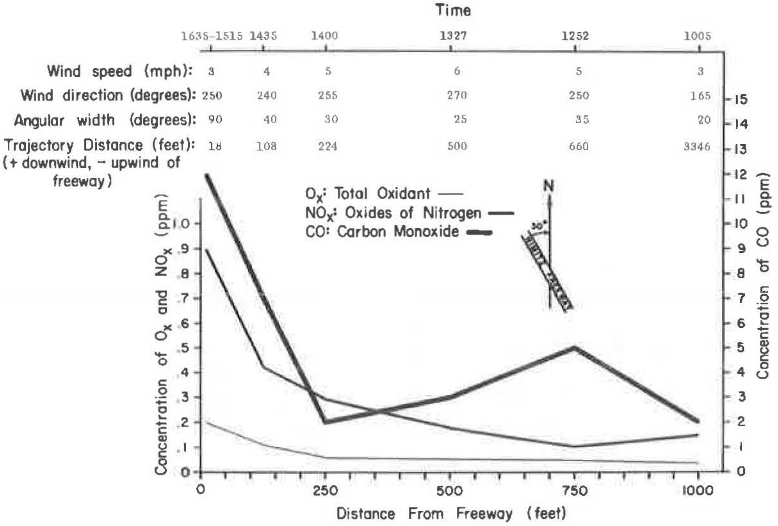
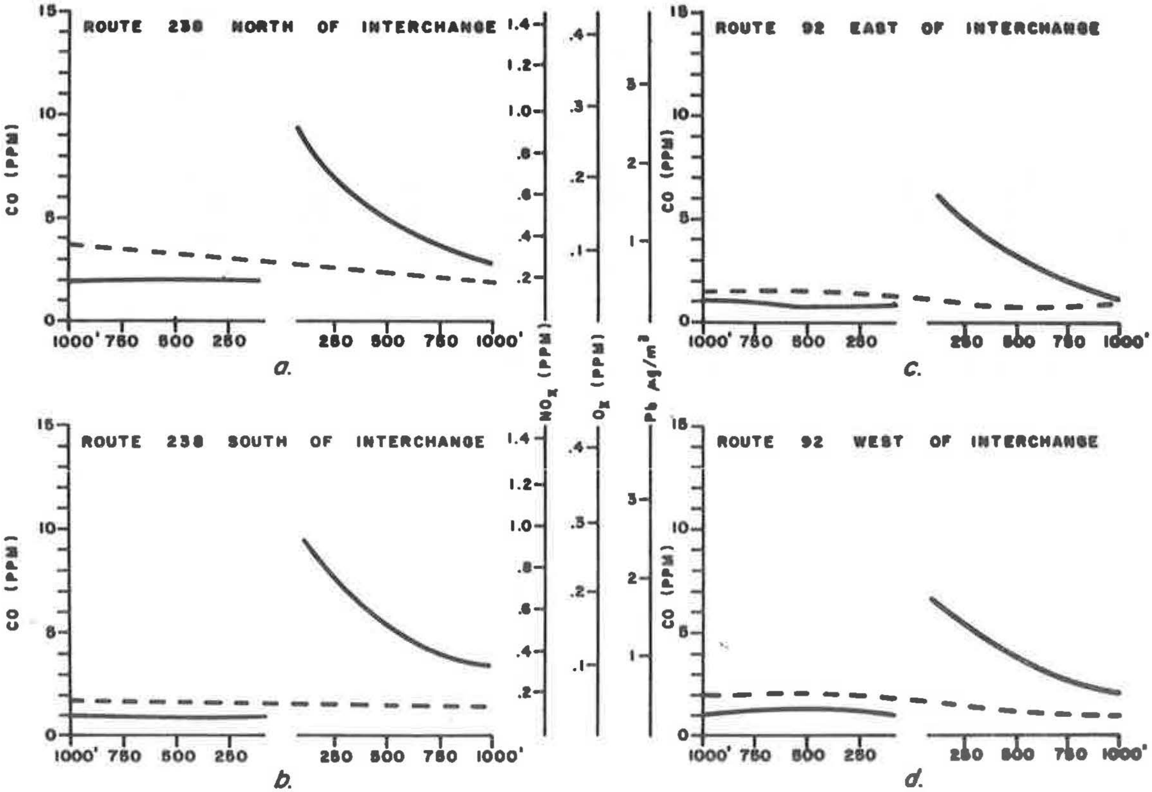


Figure 15. Projections to 1990 for air quality with and without a freeway.



validation measurements, however, were made only at one point, and we have no way of knowing the ability of the model to predict spatial variation.

It is difficult to assess the overall state of the field of air pollution modeling. The field is moving very fast, and many complex problems are involved and must be considered. In particular, the measurement phase is critically important and must be discussed in connection with the modeling effort.

First of all, it is clear that the physical rigor of all operational and research models is not high. The treatment of diffusion parameters, for instance, is usually highly arbitrary and unconnected with what we know of the physics and energetics of turbulence. In particular, diffusion coefficients are almost never given as functions of the Richardson number and surface roughness, despite extensive mircometeorological experience that this is so. Nevertheless, I think that this is of far less importance than the measurement and methodological questions to be discussed next.

Typical measurement programs in air pollution meteorology are grossly inadequate. The example discussed previously was a good state-of-the-art effort that attempted to apply, with great energy and professional competence, known techniques and standard methods to the problem. Nevertheless, it is clear that the information and results obtained are not adequate for the purpose of making future projections. Thus, a general and serious constraint must be faced. Performance must improve if reliable projections of the air quality impact of highway development are to be made.

Specifically, present measurement programs have the following faults. Air concentration of pollutants, diffusion, and standard meteorological parameters are measured, but the Richardson number is not. This deficiency ensures lack of repeatability in the results and makes an unacceptably large scatter in the data inevitable. The Richardson number has been shown to be the single most important parameter governing all micrometeorological processes. It should be a standard part of any air quality measurement program. Secondly, measurements are not adequately extensive in either time or space. Two and a half months is not a sufficiently long time to develop reliable meteorological or air quality statistics. Likewise, measurements of air quality at various distances from a highway must be simultaneous or, again, the data will not be interpretable.

It may be argued that the measures that are implied in the criticism, i.e., more sophisticated and extensive measurements, would be too expensive to fund. The counter argument is that present practices are not producing the results needed. It would be better to run far fewer measurements on a higher plane; the results would be far more useful.

Until adequate measurements are available, the question of model validation remains academic. However, considerably more effort could and should be spent in analysis of the properties of the models themselves. Intensive sensitivity studies reveal acceptable and unacceptable properties of models. In addition, such sensitivity information helps put the instrumental and observational effort in better perspective. For instance, it does not make sense to make an expensive effort to measure an input parameter that has little effect on the final model output.

SUMMARY AND CONCLUSIONS

This report has attempted to tie together the physical processes by which the microclimate is related to diffusion and transport of pollution on the microscale and mesoscale. There are four general areas in which conclusions from this review are appropriate:

1. The microclimate emerges from this discussion as a concept of considerable importance to the problem of measuring and predicting air quality. Large horizontal variations of important physical processes exist within cities. These "neighborhood contrasts" are strongly coupled to land use patterns and hence directly related to the planning processes in urban and regional governments. In particular, the evaporation rate, as indicated by relative abundance of green, freely transpiring plants, is the single most important parameter that determines the microclimatic response of a specific locality to a given radiation load and other large-scale meteorologic factors. Because

air pollution emission from motor vehicles is also closely related to land use patterns, the air pollution system as a whole is thus strongly coupled to land use. The numerical relation between land use categories and emission of vehicular air pollution will be discussed fully in another report.

2. The processes through which pollution diffuses from highways are also largely determined by the microclimate. In particular, surface roughness and atmospheric stability, as measured by the Richardson number or its equivalent, the Monin-Obukhov length, are the most important parameters controlling microscale transport and diffusion. In view of its central importance to micrometeorological and diffusion processes, an important conclusion to be drawn from this review is that measurement of the Richardson number should be a standard part of highway air quality programs. Extensive micrometeorological experience indicates that this is necessary to allow measurements made at different locations or at different times to be compared.

3. Consideration of the multitude of air pollution models that are available to estimate air quality leads to the conclusion that the models generate far more information at greater precision than is available from field measurements. In fact, the need for better and more comprehensive measurements is the most important conclusion to be drawn from this review. The measurement problem is severe because large local variability in the underlying microclimate leads to local contrasts in all processes governed by the microclimate. Hence, any measurement program must be carefully designed to ensure that the measurements are, in fact, representative of the area in question. In particular, pollution and meteorological parameters must be measured simultaneously within the study region over an adequate averaging time.

4. The state of the art of air quality modeling has been briefly reviewed in this report. The prevailing standard in the field, the Gaussian family of models, is deficient in the sense that the diffusion parameters that are used in these models are not derived directly from the physical processes that are known to dominate turbulent diffusion on the microscale, i.e., the microclimate, surface roughness, Richardson number parameter complex. More generally, it appears that far more attention needs to be paid to the properties of the models themselves. Comprehensive sensitivity analyses should be made in conjunction with model verification programs. Such information will allow better information as to the predictability of air quality and of the requirements of measurement and verification programs.

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